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Army Electronics Command
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INFLUENCE OF ELECTRODE MATERIAL ON HIGH-VOLTAGE VACUUM BREAKDOWN

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January 1968

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Abstract

The question of which electrode in a two-electrode system, the anode or the cathode, contributes most to the primary voltage breakdown mechanism, and the reasons for this contribution have been the subject of wide debate among workers in the field. Theories of breakdown that involve the anode or the cathode or both to varying extent have been proposed by Cranberg, Alpert, et al, Slivkov, Utsumi and Dalman, and others. Recent data collected by Watson, Mulcahy, and Bell and by Kranjec and Ruby, when subjected to analysis, indicate a role of the anode material in the breakdown process sufficiently clear to be applied in high-voltage vacuum tube construction. Both the analysis and data collected by Taylor and Chrepta indicate that heating of the anode owing to the flow of field emission is a primary cause of breakdown at spacings of interest in vacuum tube technology.

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INFLUENCE OF ELECTRODE MATERIAL ON HIGH-VOLTAGE VACUUM BREAKDOWN

INTRODUCTION

The voltage hold-off capability of a pair of electrodes in high vacuum is a factor that influences the design of many electron tubes ranging from moderate to super-high powers. Although many experimenters and theoreticians have applied themselves to the question of what factors affect voltage hold-off, only rough rules-of-thumb are available to the electron tube designer. One of the reasons why an analytical solution to the problem has not been obtained is the large number of variables that can affect the breakdown conditions. This aspect of the problem has been discussed in detail in other reports.[1,2] This report will deal with the question of the contribution of the electrode materials to the breakdown process. It will be shown that the breakdown in moderately spaced gaps is highly dependent upon the anode material used, leading to the conclusion that breakdown is initiated at the anode.

THEORETICAL CONSIDERATIONS

There have been many theories proposed to explain the breakdown phenomenon. A few of these are included in Table I:

TABLE I - SUMMARY OF BREAKDOWN THEORIES

Experimenter	Mechanism	Relationship	Initiating Electrode
Cranberg[3]	Clump	$V_b = k_1 d^{1/2}$	Either
Alpert, et al[4]	Critical Field	$V_b = k_2 d/\beta$	Cathode
Slivkov[5]	Vaporized Cathode Particle	$V_b = k_3 d^{5/8}/\beta^{3/8}\gamma^{1/4}$	Cathode*
Utsumi & Dalman[6]	Small Gaps - Critical Field	$V_b = k_2 d/\beta$	Cathode
	Large Gaps - Anode Heating	$I_b = k_4 d^{-1/2}$	Anode
Chrepta & Taylor[7]	Anode Heating	$V_b = k_5 d^a$	Anode

*Anode material on cathode initiates arc.

where k_1, k_2, k_3, k_4, and k_5 = constants of proportionality,

β = cathode field-enhancement factor,

γ = anode field-enhancement factor,

$n \leq 0.6$ = empirically determined exponent,

V_b = voltage at breakdown,

and I_b = current at breakdown.

These theories have been selected because they serve to illustrate the aspects of the problem that must be reconciled before we can expect universal acceptance of a breakdown theory. To be accepted, the breakdown theory must present a self-consistent physical picture of the breakdown process. This should, in turn, lead to an analytical relationship between some measurable quantity, such as voltage at breakdown or current at breakdown, and a characteristic feature of the gap, which will be of practical use in design situations.

A review of the relationships shown in Table I would lead the uninitiated to conclude at first glance that it should be relatively simple to discriminate between these various possible theories since there is such a wide variation in the exponent involving the gap spacing, varying as it does from a half to one. One is inclined to state that the voltage hold-off data should answer this question without great difficulty. If actual breakdown data are examined, however, this optimism is soon dispelled because of two reasons. The first is illustrated by a plot of the voltage breakdown versus spacing calculated from data recently published by Kranjec and Ruby[8] for a large number of materials, shown in Fig. 1, namely, the large spread in the data:

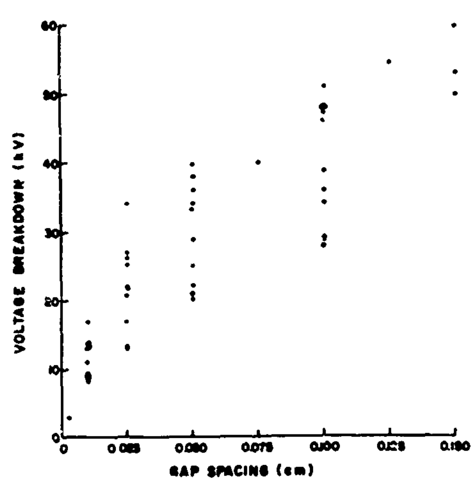


Fig. 1 Breakdown Voltage Vs. Gap Spacing for Various Materials

Although a good portion of this spread is attributable to the different materials used as both cathode and anode, the spread within materials also contributes to the scatter. The data can, however, be fitted to a relationship of the form

$$V_b = kd^n$$

and values can be obtained for the constants k and n from the Kranjec and Ruby data with a fair degree of correlation. When one attempts to check the value obtained for the exponent, n, against the values contained in Table I, one encounters the second difficulty. One finds that the factor β used by Alpert, et al[4] as a measure of the enhancement of the gross field by a protuberance on the cathode is not a constant but is a function of gap spacing. We find a relationship of the form

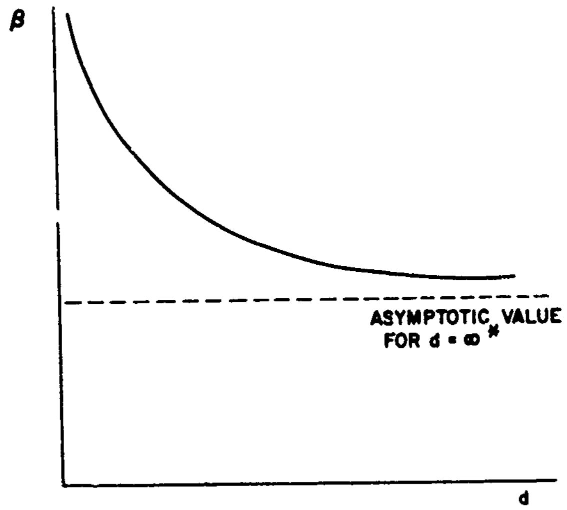
$$\beta = cd^m$$

where the value obtained for the exponent $m \approx 1 - n$. Substituting this value for β in the Alpert voltage-breakdown relationship,

$$V_b = \frac{k_2 d}{cd^{1-n}} = kd^n ,$$

which also fits the empirical data. The range in the exponent predicted by theory is thus reduced from the original spread of $\frac{1}{2}$ to 1 to a range of $\frac{1}{2}$ to 5/8 or less, since the Slivkov relationship also includes the spacing dependent field-enhancement factor. The use of the value of the exponent n as a determining factor for validating a theory is, therefore, difficult. Because of this lack of sensitivity, we must rely on the self-consistency of the physical picture presented by the theory as a guide to the selection of the theory.

The critical-field theory does not present a clear physical picture of the breakdown process except at the small gap spacings, where the value of the field-enhancement factor, β, is within the bounds of actual measurements made of the geometries of whiskers found on the cathode. As the gap spacing is increased, however, the theory requires the enhancement factor to continually increase with spacing. For a fixed geometry protuberance, however, the value of the field-enhancement factor would decrease with spacing, as shown in Fig. 2:



*For examples of β calculated for assumed geometries with the anode at infinity, see Vibrans - Lincoln Lab Report #353, "Field Emission in Vacuum Voltage Breakdown."

Fig. 2 Variation of β with a Gap Spacing for a Fixed Geometry Protuberance.

To meet the growth-in-β requirements dictated by the critical field theory, it would, therefore, be necessary for the size of the whisker to increase with spacing or for the radius of the whisker to decrease with spacing. This picture is not self-consistent, since there is no reason for a whisker to grow longer or to become sharper as you tend to decrease the forces acting upon it. Thus, although we cannot explain the behavior of β at this time, we must for these and other reasons reject the critical-field theory as the cause of voltage breakdown at large gap spacings.

The data presented by Utsumi and Dalman[6] at the Second Symposium on Insulation of High Voltages in Vacuum include a number of errors in the printed version, so that the relationship that was shown in Table I is not considered to be accurate. In addition, since the relationship is in terms of the current from a single point, it is not a practical breakdown criterion because it can neither be measured nor controlled. Utsumi and Dalman, however, presented measured data showing that the beam diameter from a single point would increase with gap separation leading to an increase in the temperature at the center of the anode spot because of this beam, even though the power density and total power were decreased. Supplementing these results, we have the experimental data taken by two of the authors, indicating that breakdown was being approached when a point on the anode emitted a

specific level of infrared radiation indicative of a constant temperature criterion for breakdown.

ANALYSIS OF EXPERIMENTAL DATA

Since anode heating because of a hot spot on the anode was indicated by these results, the data collected by Kranjec and Ruby were analyzed using multiple regression techniques with the following model:

$$V_b = k\, C_s^{\,a} T_v^{\,b} d^{n}$$

or

$$\ln V_b = \ln k + a \ln C_s + v \ln T_v + n \ln d$$

where C_s = specific heat,

T_v = temperature at which a vapor pressure of 10^{-5} torr is obtained,

and k, a, b, n = constants to be determined by the regression analysis.

Using the techniques of Ezekiel and Fox[9] the least squares fit to this multi-variable equation is

$$V_b = 300\, C_s^{\,0.31}\, T_v^{\,0.28}\, d^{0.57}$$

where V_b is in kilovolts,

C_s is in cal/g,

T_v is in $^\circ K \times 10^{-3}$,

and d is in centimeters.

The standard errors of estimate (σ_a, σ_b, σ_n) around the most probable values obtained from the analysis using these techniques are shown below:

$$a \pm 1\sigma_a = 0.31 \pm 0.09 \approx 1/3$$

$$b \pm 1\sigma_b = 0.28 \pm 0.08 \approx 1/4$$

$$n \pm 1\sigma_n = 0.57 \pm 0.03 \approx 4/7\,.$$

Testing for a null hypothesis that the true value of the exponent n for a sample of the size involved is

Null Hypothesis #1 - $n \leq 1/2$

Null Hypothesis #2 - $n \geq 5/8$

$$Z = \frac{n - n_{th}}{\sigma_n}\sqrt{D.F.}$$

$$Z_1 = \frac{0.57 - 0.5}{0.03}\sqrt{43} = 15.3$$

$$Z_2 = \frac{0.57 - 0.625}{0.03}\sqrt{43} = 12.02$$

Z_{crit} = 3.551 at 99.95% level of significance,

indicating that both of these null hypotheses would be rejected at the 0.01% level of significance.

The data, therefore, do not warrant the conclusion that the empirical value of the coefficient is either 1/2 or 5/8 but rather an intermediate value. The value of 0.57 is interestingly smaller than the value of 0.60, which was the smallest exponent of the voltage versus gap spacing for a constant temperature found by two of the authors[6] while maintaining the voltage level below that required to break down the gap.

In addition to examining the value of the exponent of gap spacing, a further test of the Slivkov model (which is based on the conversion of the kinetic energy of a charged particle into vaporized material) was made by calculating the fit of the Kranjec and Ruby data to Slivkov's relationship, which can be expressed as

$$V_b = k\,\delta^{1/4}\,L_{sub}^{3/8}\,A^{-1/4}\,d^{5/8}$$

where δ = density,

L_{sub} = heat of sublimation,

and A = atomic weight.

Not only was the overall correlation coefficient poorer than that found for the anode heating model, but the material parameters showed almost no correlation with the voltage breakdown. The results are summarized in Table II:

TABLE II - REGRESSION AND CORRELATION COEFFICIENTS

Anode Heating Model $V_b = kC_s^a\ T_v^b\ d^n$			Slivkov Model $V_b = k\delta^c\ L_{sub}^e\ A^f\ d^n$		
Regression		Correlation	Regression		Correlation
Measured	Theoretical		Measured	Theoretical	
a. 0.31	?	67.9%			
b. 0.28	?	55.3%			
c.			0.015	0.25	6.5%
e.			0.254	0.375	19.5%
f.			-0.315	-0.25	10.6%
n. 0.57	?	93.9%	0.57	0.625	86.4%
k. 300			777		
Multiple Correlation		94.8%			93.9%

Although the Kranjec and Ruby data were collected with identical materials used for the cathode and anode, the model used to arrive at the equation to which the data were fitted was based on the heating of the anode by field-emission currents. To further verify this anode heating model, it was decided to take the equation derived from the Kranjec and Ruby data and apply it to the data collected by Mulcahy, et al,[10] in thirty-two separate experiments in which tests were performed at specific combinations of seven variables, each taken at two levels. One of the variables in this experiment is the anode material tested at two levels, i.e., copper and a titanium, molybdenum, aluminum alloy (Ti7Al4Mo). Assuming that the voltage breakdown relationship is

$$V_b = k'\ C_s^a\ T_v^b\ d^n$$

where
$$k' = k + u\ c_1\ X_1 + c_2\ X_2 + \dots\ c_j\ X_j$$
$$+ c_{12}\ X_1X_2 + c_{13}\ X_1X_3 + \dots c_{(j-1)j}X_{(j-1)}X_j$$

then $$V_b = k\, C_s^{\,a}\, T_v^{\,b}\, d^n + \left(\mu + c_1 X_1 + \cdots c_{(j-1)j} X_{(j-1)} X_j\right) C_s^{\,a}\, T_v^{\,b}\, d^n$$

and $$\text{Residual} = \frac{V_b - k\, C_s^{\,a}\, T_v^{\,b}\, d^n}{C_s^{\,a}\, T_v^{\,b}\, d^n} = \mu + c_1 X_1 + \cdots c_{(j-1)} X_{(j-1)} X_j \,.$$

If the data from the thirty-two experiments are thus corrected for the effects caused by anode heating by the calculation shown, it is expected that the residual can be analyzed for the relationship to the variables of the experiment using standard techniques, such as the Yates Algorithm.[11] Furthermore, if a significant difference in breakdown voltage is found for the two different anode materials using the original data, and if the source of this significance is the anode heating factors contained in the correction, then the residual breakdown voltage values should show no contribution because of this anode effect. The remaining factors of importance should not be grossly disturbed because of this treatment. The results of the original analysis and the analysis of the modified data, tabulating only those factors found to be significant in the order of importance, are shown in Table III:

TABLE III - RESULTS OF ANALYSIS OF RESIDUALS
(Mulcahy Data)

Original Data		Modified Data	
Titanium Alloy Anode	> Copper Anode	Spherical Anode	> Planar Anode
Spherical Anode	> Planar Anode	Spherical Cathode	> Planar Cathode
Spherical Cathode	> Planar	Titanium Alloy Spherical Anode	> Others*
System Bakeout	> Electrode Only Bakeout	System Bakeout	> Electrode Only Bakeout
Titanium Alloy Spherical Anode Combination	> Others*		

* This is an interaction between two variables, i.e., a term of the type $C_{(j-1)j} X_{(j-1)} X_j$.

CONCLUSIONS

The analysis, therefore, indicates that the equation derived from the Kranjec and Ruby data fits the Mulcahy, et al, data and completely accounts for the effect of the differences in anode material. The model equation derived is proposed as a tentative equation that should be further explored, particularly on programs such as that being carried out by Mulcahy, Denholm, and Watson under ARPA sponsorship.[10] Until the full data are collected,

it is concluded that the Ti7Al4Mo alloy improves voltage hold-off sufficiently over copper to recommend its use for the positive portions of electrodes, such as on facing sections of non-current-intercepting modulator anodes or accelerating electrodes, where thermal conductivity of copper is not essential.

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13. ABSTRACT

The question of which electrode in a two-electrode system, the anode or the cathode, contributes most to the primary voltage breakdown mechanism, and the reasons for this contribution have been the subject of wide debate among workers in the field. Theories of breakdown that involve the anode or the cathode or both to varying extent have been proposed by Cranberg, Alpert, et al, Slivkov, Utsumi and Dalman, and others. Recent data collected by Watson, Mulcahy, and Bell and by Kranjec and Ruby, when subjected to analysis, indicate a role of the anode material in the breakdown process sufficiently clear to be applied in high-voltage vacuum tube construction. Both the analysis and data collected by Taylor and Chrepta indicate that heating of the anode owing to the flow of field emission is a primary cause of breakdown at spacings of interest in vacuum tube technology. (Authors)

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